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14. ABSTRACT

Fundamental research issues and novel designs of Sb-based superlattice photodetectors are reported. These include the following:
Accomplishment 1. Growth of new InAs/GaSb type-II superlattice material using MOCVD. We report the improved SL quality based on different interfacial layers (IF) and detector results using new growth schemes.
Accomplishment 2. Demonstration of the first MOCVD grown InAs/GaSb type-II superlattice photodiodes. We

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Report Title

Antimony-Based Type-II Superlattice Photodetectors

ABSTRACT

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Accomplishment 2. Demonstration of the first MOCVD grown InAs/GaSb type-II superlattice photodiodes. We have characterized the photodiodes' I-V curve, responsivity, and detectivity with improved performance.
Accomplishment 3. Realization of the first InAs/InAsSb type-II superlattice structure grown by MOCVD. We have measured the structure's absorption spectra.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1.Y. Huang, J. H. Ryou, R. D. Dupuis, A. Petschke, M. Mandl, and S. L. Chuang, "InAs/GaSb type-II superlattice structures and photodiodes grown by metalorganic chemical vapor deposition," Appl. Phys. Lett. 96, 251107 (2010).
2. A. Petschke, M. Mandl, S. L. Chuang, Y. Huang, J. H. Ryou, and R. D. Dupuis, "Metal-organic chemical vapour deposition growth of InAs/GaSb type-II superlattice photodiodes," Elec. Lett. 46, 1151 (2010).
3. S. Mou, J. V. Li, and S. L. Chuang, "Quantum efficiency analysis of InAs/GaSb type-II superlattice photodiodes," IEEE J. Quant. Electron. 45, 737 (2009).
4. J. V. Li, C. J. Hill, J. Mumolo, S. Gunapala, S. Mou, and S. L. Chuang, "Mid-infrared type-II InAs/GaSb superlattice photodiodes towards room temperature operation," Appl. Phys. Lett. 93, 163505 (2008).
5. S. Mou, A. Petschke, Q. Lou, S. L. Chuang, J. V. Li, and C. J. Hill, "Midinfrared InAs/GaSb type-II superlattice tunneling photodetectors," Appl. Phys. Lett. 92, 153505 (2008).
6. S. Mou, J. V. Li, S. L. Chuang, "Surface channel current in InAs/GaSb type-II superlattice photodiodes," J. Appl. Phys. 102, 066103-1 to -3 (2007).
7. J. V. Li, S. L. Chuang, E. Aifer, and E. M. Jackson, "Surface recombination velocity reduction in type-II InAs/GaSb superlattice photodiodes due to ammonium sulfide passivation," Appl. Phys. Lett. 90, 223503-1 to -3 (2007).
8. X. B. Zhang, J. H. Ryou, R. D. Dupuis, C. Xu, S. Mou, A. Petschke, K. C. Hsieh, and S. L. Chuang, "Improved surface and structural properties of InAs/GaSb superlattices on (001) GaSb substrate by intoducin an InAsSb layer at interfaces," Appl. Phys. Lett. 90, 131110 (2007).
9. X. B. Zhang, J. H. Ryou, R. D. Dupuis, S. Mou, S. L. Chuang, C. Xu, and K. C. Hsieh, "Metalorganic chemical vapor deposition of metamorphic InAs-GaSb superlattices on (001) GaAs substrates for mid-IR photodetector applications," J. Crystal Growth 287, 545 (2006).
10. X. B. Zhang, J. H. Ryou, R. D. Dupuis, A. Petschke, S. Mou, S. L. Chuang, C. Xu, and K. C. Hsieh, "Metalorganic chemical vapor deposition of high-quality InAs/GaSb Type II superlattices on (001) GaAs substrates," Appl. Phys. Lett. 88, 072104 (2006).

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. Zhang, X.B.; Petschke, A.; Mou, S.; Xu, C.; Ryou, J.H.; Chuang, S.L.; Hsieh, K.C.; Dupuis, R.D.; Metalorganic Chemical Vapor Deposition Growth of High-Quality InAs/GaSb Type II Superlattices for Mid-IR Photodetector Applications, International Conference on Indium Phosphide and Related Materials Conference Proceedings, pp. 415-419, May 7-11, 2006.

2. S. Mou, J. Li, and S. L. Chuang, "Quantum efficiency of an InAs/GaSb type-II superlattice photodiode," Am. Phys. Soc. March Meeting, March, 2007.

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Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

S. L. Chuang, J. V. Li, and R. Q. Yang, Interband Cascade Detectors, US Patent #7,282,777, October 16, 2007.

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NAME	PERCENT_SUPPORTED
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Adam Petschke	0.25
Yong Huang	0.25
Martin Mandl	0.10
Q. Lou	0.25
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Total Number:	**5**

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FTE Equivalent:	**0.10**
Total Number:	**1**

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NAME	PERCENT_SUPPORTED	National Academy Member
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Russell D. Dupuis	0.00	Yes
FTE Equivalent:	**0.10**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

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The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
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Names of Personnel receiving masters degrees

NAME	
Q. Lou	
Martin Mandl	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Adam Petschke	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED	
J. H. Ryou	0.10	No
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5 **Interband Cascade Detectors**

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Patent Filed in Foreign Countries? (5d-2) N

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Final report: September 5, 2006 to August 31, 2010. (Project dates: 9/05/2006 to 3/04/2010)

ARO Program Director: Dr. William Clark

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Project Title: Antimony-based type-II superlattice photodetectors

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Post-doctoral researcher: X. Zhang, GIT
Research engineer: J. H. Ryou, GIT

Abstract:

Fundamental research issues and novel designs of Sb-based superlattice photodetectors are reported. These include the following:

Accomplishment 1. Growth of new InAs/GaSb type-II superlattice material using MOCVD. We report the improved SL quality based on different interfacial layers (IF) and detector results using new growth schemes.

Accomplishment 2. Demonstration of the first MOCVD grown InAs/GaSb type-II superlattice photodiodes. We have characterized the photodiodes' I-V curve, responsivity, and detectivity with improved performance.

Accomplishment 3. Realization of the first InAs/InAsSb type-II superlattice structure grown by MOCVD. We have measured the structure's absorption spectra.

Progress and accomplishments:

This report focuses on progress of the last year since September 1, 2009. The progress of the previous years has been reported in the annual reports each year.

Accomplishment 1: Growth of new InAs/GaSb type-II superlattice material using MOCVD

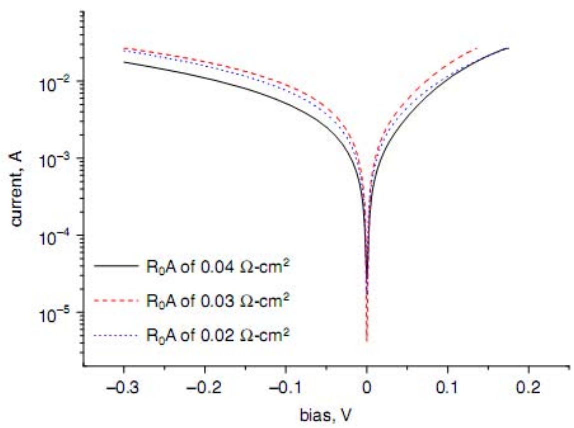
Previously, the demonstration of InAs/GaSb type-II superlattice (T2SL) materials for mid-infrared (IR) devices was done with samples grown with molecular beam epitaxy (MBE). While these devices have been shown to perform well, an important step in InAs/GaSb T2SL development is growth using metal-organic chemical vapor deposition (MOCVD), which is the preferred method of growth in manufacturing. We have produced and refined such a process as part of an effort to make the new material composition more appealing for widespread use, in place of current alternatives such as mercury cadmium telluride (MCT) detectors.

As we reported earlier, an effective growth method was investigated. Epitaxial growth of InAs/GaSb T2SL structures was carried out in a Thomas Swan MOCVD reactor equipped with a close-coupled showerhead growth chamber at a pressure of 100 Torr. Trimethylindium [TMIn, $In(CH_3)_3$ and triethylgallium [TEGa, $Ga(C_2H_5)_3$] were used as column III precursors and trimethylantimony [TMSb, $Sb(CH_3)_3$] and arsine (AsH_3) were used as column V precursors. The dopant precursors include disilane (Si_2H_6) for n-type silicon Si doping and diethylzinc [DEZn, $Zn(C_2H_5)_2$] for p-type zinc Zn doping. SL and device structures were grown on p-type (001) GaSb substrates, with the GaSb buffer being grown at 600 °C and the InAs/GaSb SL at 530 °C. Our previous results demonstrated that a combined interfacial (IF) growth scheme utilizing 1 monolayer (ML) of InAsSb + 1 ML InGaSb was the most effective, compensating for strain and providing superior surface morphology (RMS roughness of 0.125 nm determined via AFM). Doping of the *p*-SLs was performed using Zn, and easily reached a maximum free hole concentration of 3×10^{19} cm^{-3}. The doping of the *n*-SLs was more challenging, but with a high concentration (~150 ppm) of silane we were able to reach a maximum concentration of 2×10^{18} cm^{-3}, sufficient for a detector application.

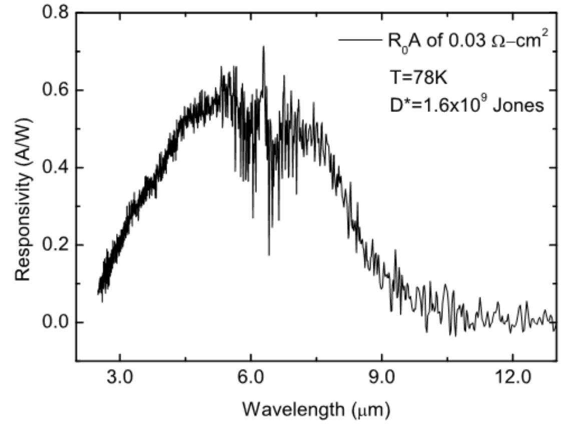
Accomplishment 2: Demonstration of the first MOCVD grown InAs/GaSb type-II superlattice photodiodes

As mentioned in the previous report, we demonstrated for the first time photodetectors made from MOCVD grown InAs/GaSb T2SLs. The newly grown samples with mixed IF growth were processed into detectors by Chuang's group at UIUC. The detectors were processed into mesas using citric acid based wet etching. The mesas ranged in size from 150×150 µm^2 to 400×400 µm^2. The top and bottom metals (Ti/Pt/Au) were deposited using e-beam evaporation. Since Ti/Pt/Au makes an ohmic contact with both n+ InAs and p+ GaSb, no anneal was needed. No passivation scheme was used for these samples.

The results of the new MOCVD grown photodetectors are shown in Figs. 1 and 2. . The measurements were taken with the use of a Janis cryostat, which allows for temperature controlled measurements from 4K to room temperature. The electrical measurements were conducted at 78K. Fig. 1(a) shows the I-V-curve of three different detectors. The devices show R_0A-products of around 3×10^{-2} Ωcm^2, which is less then two orders of magnitude lower than state of the art type-II InAs/GaSb-based devices for this wavelength without any passivation treatment. The responsivity curve is shown in Fig. 1(b). The peak responsivity is ~0.6 A/W at 6



(a)



(b)

Fig.1: (a) The dark I-V curves for three typical detectors of size 400 x 400 μm^2 at 78 K. The R_0A products are also shown. (b) Responsivity curve of one detector for the size of 400 x 400 μm^2. All measurements taken at 78 K.

µm, neglecting interference due to the atmosphere. The peak detectivity is 1.6 x 10^9 Jones, which is less than one order of magnitude lower than the detectivity of comparable devices such as MCT. The temperature dependence of the R_0A product is shown in Fig. 2. At high temperatures, the device fits an exponential trend with an activation energy of $E_g/2$, implying that the device is limited by generation-recombination.

Accomplishment 3: Realization of the first InAs/InAsSb type-II superlattice structure grown via MOCVD (Collabroation between R. D. Dupuis at Geogia Tech, S. L. Chuang at UIUC, and Yong-Hang Zhang at ASU**).**

An alternative to InAs/GaSb based devices is the use of InAs/InAsSb, which can be designed for virtually zero strain. This is a stark contrast to the complex IF growth schemes needed to grow InAs/InAsSb on the same GaSb substrate. Previously, the InAs/InAsSb material composition was used primarily for light-emitting applications. This task is a recent collabration among three groups: R. D. Dupuis at Geogia Tech, S. L. Chuang at UIUC, and Yong-Hang Zhang at ASU.

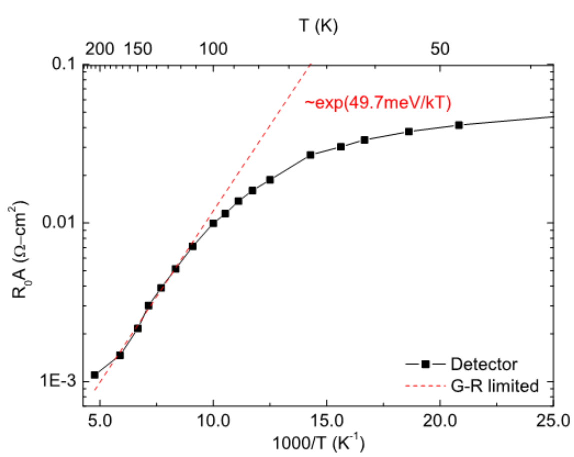
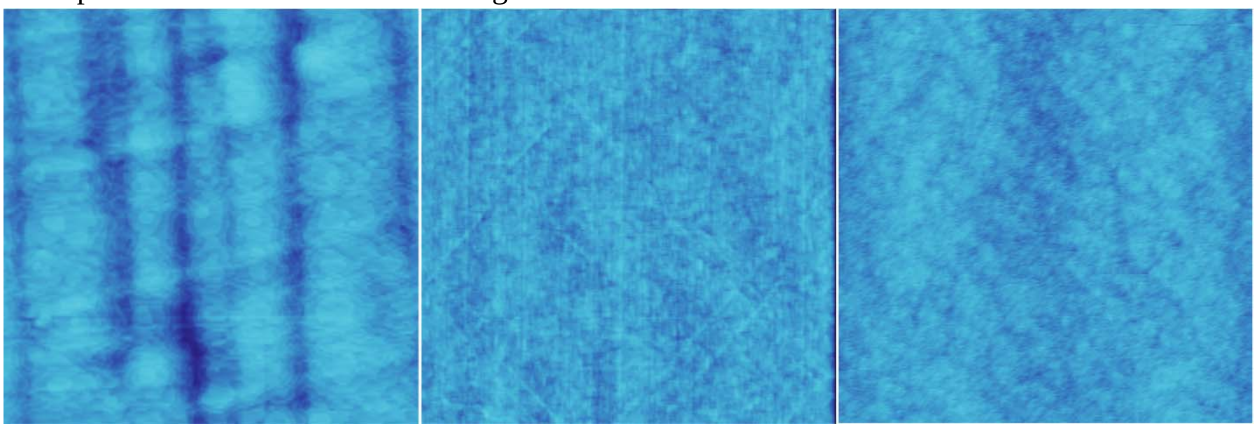


Fig.2: The Arrhenius plot for the R0A product of a typical detector of size 200 x 200 μm^2. The device is generation-recombination (G-R) limited at high temperatures.

The InAs and InAsSb single layers were calibrated at 500 °C. Fig. 3 shows the XRD ω-2θ scans for a 110 nm InAs layer and a 65 nm $InAs_{0.75}Sb_{0.25}$ layer. The XRD results indicate clearly the tensile strain in the InAs layer and compressive strain in the $InAs_{0.75}Sb_{0.25}$ layer on GaSb substrates. The AFM images for these two layers are displayed in figs. 3(a) and 3(b), respectively. The tensile-strained InAs exhibits a surface undulation with a RMS surface roughness of ~0.296 nm, while the compressive-strained $InAs_{0.75}Sb_{0.25}$ shows low-density cross-hatch patterns with a RMS surface roughness of ~0.126 nm.



(a) (b) (c)

Fig.3: 20 × 20 μm^2 AFM images for (a) InAs, (b) $InAs_{0.75}Sb_{0.25}$, and (c) 100-period InAs/$InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm) T2SLs. (a) is in 10 nm height scale and (b) and (c) are in 5 nm scale. The RMS surface roughness values from (a) to (c) are 0.296 nm, 0.126 nm, and 0.108 nm, respectively.

The InAs/InAsSb T2SL structures were grown at 500°C after calibration of the single layers. Because of the absence of Ga in the SL layers, the interfacial control was found to be more straight-forward in these structures. A 3-s AsH_3 flow was introduced after InAs layer growth and a 1-s AsH_3 flow was followed after InAsSb layer growth. Fig. 3(c) is the surface morphology of a 100-period InAs/$InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm) SB T2SL structure. Excellent surface morphology with a RMS surface roughness as low as 0.108 nm was obtained for this 1-μm-thick T2SLs. Shown in figure 4 are the XRD $\omega/2\theta$ scans for the 100-period

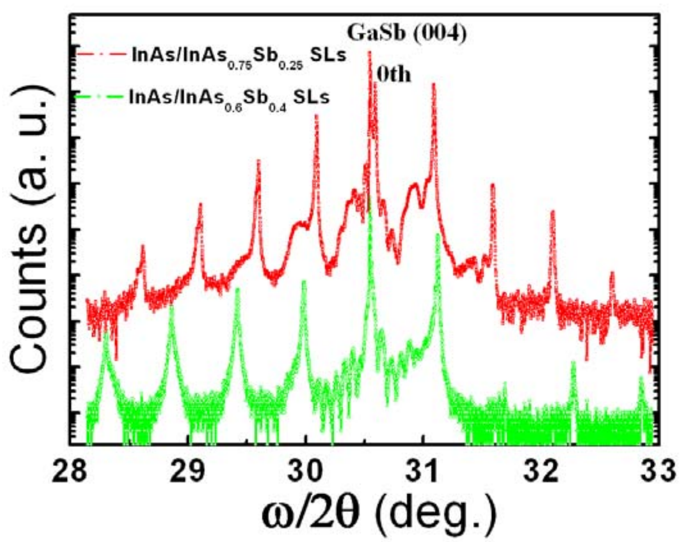


Fig.4: XRD ω-2θ scans near (004) diffraction for the 100-period InAs/$InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm) T2SLs and the 50-period InAs/$InAs_{0.6}Sb_{0.4}$ (7.0 nm/2.0 nm) T2SLs.

$InAs/InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm) SB T2SLs and a 50-period $InAs/InAs_{0.6}Sb_{0.4}$ (7.0 nm/2.0 nm) SB T2SLs. Narrow and intense satellite peaks are clearly visible, indicating superior structural quality and sharp interfaces. The average strains revealed from the 0^{th}-order peaks are only 0.07 % and 0.02 %, respectively, which are nearly strain-balanced.

The absorption coefficients for the InAs/GaSb (4.5 nm/ 2.2 nm), $InAs/InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm), and $InAs/InAs_{0.6}Sb_{0.4}$ (7.0 nm/2.0 nm) T2SLs are summarized in Fig. 5. Combined IF layers were used in the InAs/GaSb T2SLs. The absorption measurements were carried out at room temperature from 0.06 eV to 0.65 eV using an infrared variable angle spectroscopic ellipsometer. The designed cut-off wavelengths are λ~10 μm (124 meV) for the InAs/GaSb T2SLs, λ~8 μm (155 meV) for the $InAs/InAs_{0.75}Sb_{0.25}$ T2SLs, and λ~14 μm (88 meV) for the

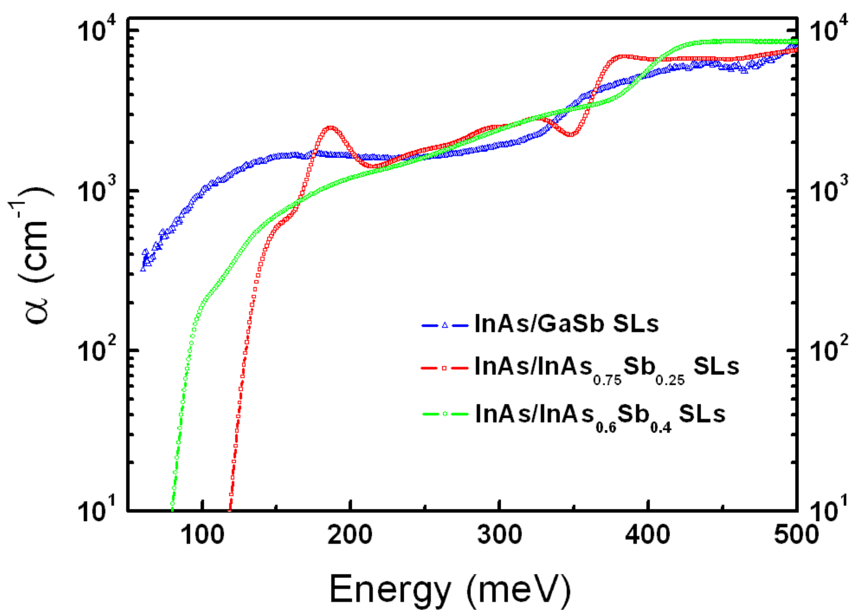


Fig.5: Absorption coefficients for the 30-period InAs/GaSb (4.5 nm/2.2 nm) T2SLs, the 100-period $InAs/InAs_{0.75}Sb_{0.25}$ (7.0 nm/3.3 nm) T2SLs and the 50-period $InAs/InAs_{0.6}Sb_{0.4}$ (7.0 nm/2.0 nm) T2SLs.

InAs/InAs0.6Sb0.4 T2SLs. The absorption coefficients are similar for these two types of T2SLs. The cut-off wavelengths and corresponding effective bandgap energies were determined to be 12.4 μm (100 meV), 9 μm (138 meV), and 13.5 μm (92 meV) for these T2SLs, which are in reasonable agreement with the designed values. It should be pointed out that the InAs/InAsSb

T2SLs have steeper cut-off than the InAs/GaSb T2SLs, which is possibly due to the thinner absorption layer and the use of IF layers in the InAs/GaSb T2SLs. These results indicate that InAs/InAsSb SB T2SLs are an important alternative to InAs/GaSb T2SLs for LWIR detection and are more suitable for MOCVD growth.

References:

[1] Y. Huang, J. H. Ryou, R. D. Dupuis, A. Petschke, M. Mandl, and S. L. Chuang, “InAs/GaSb type-II superlattice structures and photodiodes grown by metalorganic chemical vapor deposition,” *Appl. Phys. Lett.* **96**, 251107 (2010).

[2] A. Petschke, M. Mandl, S. L. Chuang, Y. Huang, J. H. Ryou, and R. D. Dupuis, “Metal-organic chemical vapour deposition growth of InAs/GaSb type-II superlattice photodiodes,” *Elec. Lett.* **46**, 1151 (2010).

[3] Y. Huang, J.-H. Ryou, R.D. Dupuis, V.R. D’Costa, E.H. Steenbergen, Y.-H. Zhang, A. Petschke, M. Mandl, S.-L.Chuang, “Epitaxial growth and characterization of InAs/GaSb and InAs/InAsSb type-II superlattices on GaSb substrates by metalorganic chemical vapor deposition for long wavelength infrared photodetectors,” *J. Crystal Growth* (to be submitted).